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Topology optimization for simplified structural fire safety

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ABSTRACT

Topology optimization is applied in an idealized structural fire safety model, where the minimum compliance problem is constrained by temperature-controlled structural degradation. The constraint ensures a certain structural stiffness after a prescribed time. As this time period is extended, resulting optimized topologies tend to become thicker or introduce redundant members that can take over when structural parts near the origin of the fire lose their load carrying capability. Hence, the structural degradation model acts as an erosion operator on the topology and indirectly enforces a minimum length scale on the final designs.

1. Introduction

1.1. Object and motivation

Structural design aims at providing sufficient load carrying capacity for the Ultimate Limit State (ULS) and appropriate stiffness for the Serviceability Limit State (SLS). In addition, structural integrity against accidental events, such as fire, explosions, and unexpected local failures, must be ensured. This third requirement is included in the Eurocodes [1] as an accidental design situation and commonly referred to as the Accidental Limit State (ALS). It is generally difficult to account for all three limit state requirements in the early stages of structural design. Therefore, optimizations associated with the ULS and SLS are typically performed first, and later, if necessary, the design is adapted and verified for accidental actions. Such amendments in the late stages of the design process may affect the optimality of the already optimized design. This is especially true for the case of fire design, because the design characteristics of fire resistant elements often are opposite to those of elements optimized for stiffness and resistance at the SLS and ULS.

In order to clarify the latter statement, a typical design optimization problem can be considered, where, given a certain amount of steel, the optimal shape of a section profile is sought. Table 1 provides an overview of profiles with the most common geometrical shapes and the same area (small deviations in the values are given by limitations on the dimensions of existing profiles). For the sake of simplicity, only sections having the same maximum dimensions (L_x, L_y) along the two principal axes are considered and analyzed with respect to the resistance to a positive bending moment. The HEB (European wide flange H-beams) profile has by far the highest elastic modulus of resistance W_{el}, showing that the best way of distributing the steel for maximizing the resistance at ambient condition is to concentrate it at the top and bottom of the domain, where the elastic stresses are the highest. On the other hand, concentrating the steel closer to the core of the profile, such as in a triangular- or diamond-shaped profile, yields a high plastic benefit, intended as ratio between the plastic and elastic modulus of resistance W_{pl}/W_{el}. However, the shape that yields the highest plastic modulus of resistance is still the HEB profile, which is therefore optimal from the point of view of both SLS and ULS. This is not the case anymore when fire is considered, because the concentration of the steel area towards the core of the profile has a double effect, as it also reduces the ratio between the exposed perimeter and the area of the profile (P/A), referred in the following as the section factor. Hereby, the temperature of the profile for a given time of fire exposure is also reduced and the degradation of the steel's mechanical properties is less severe. If a standard fire exposure of 30 min is considered, a circular shape is the optimal profile, closely followed by the triangular-shaped profile. On the other hand, the HEB profile has by far the highest section factor and the most severe reduction of strength $f_y(t = 30')/f_y$, as well as one of the lowest fire resistances (followed only by the hollow circular and rectangular profiles). In the example, the strength

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Table 1
Elastic, plastic, and fire resistance properties for profiles with different shapes. f_y denotes yield stress and M_{pl} denotes sectional plastic moment.

Profile shape	$L_y = L_x$ [m]	thickness [m]	A [m^2]	W_{el} [m^3]	W_{pl} [m^3]	W_{pl}/W_{el} [–]	P/A [m^{-1}]	$f_y(t=30')/f_y$ [–]	$M_{pl}(t=30')/f_y$ [m^3]
CIRCULAR	1.35E−01	–	1.43E−02	2.41E−04	4.09E−04	1.7	29.7	50%	2.06E−04
ISOSC. TRIAN.	1.70E−01	–	1.45E−02	4.09E−04	9.70E−04	2.4	38.1	21%	2.03E−04
SQUARED	1.20E−01	–	1.44E−02	2.88E−04	4.32E−04	1.5	33.3	34%	1.46E−04
HEB300	3.00E−01	0.11E−01	1.43E−02	1.61E−03	1.79E−03	1.1	123.4	7%	1.20E−04
HOLLOW CIRC.	2.13E−01	2.50E−02	1.48E−02	6.23E−04	7.92E−04	1.3	45.3	13%	1.06E−04
HOLLOW RECT.	2.00E−01	2.00E−02	1.44E−02	7.87E−04	9.76E−04	1.2	55.6	9%	9.16E−05

reduction for the 2% stress, i.e. effective yielding, is calculated with the formula suggested by Hertz [2].

As a result, an optimization based on SLS or ULS designs would require a significant amount of insulation in order to provide the HEB profile with sufficient resistance in case of a fire (right arrow on second row of Fig. 1). Therefore, steel profiles are typically insulated by fire-resistant panels, intumescent paints or spray-on plasters. The first method deceives the aesthetic aspects of the optimized structures, the second nullifies the original economic benefits, and the third is non-ideal from both an aesthetic and an economic perspective. Conversely, an optimization based exclusively on the fire resistance would hardly comply with the stiffness or ULS resistance requirements and ultimately lead to a cumbersome increment of the cross-section dimensions and an uneconomical design of the profiles. This is exemplified by the left arrow on the third row of Fig. 1, where a circular profile is chosen from an optimization based only the fire resistance and then the dimension of the profile is increased for satisfying the ULS verification. The optimal profile can only be identified by performing the optimization at a later design stage, i.e. after both stiffness and fire resistance requirements have been verified. By assuming a maximum strength reduction factor of 30% (on the basis of a typical reduction factor of the load for the fire case [3]), a later optimization of either the resistance (max M_{pl}) or the fire resistance (max $M_{pl}(t=30'))$ would lead to a selection of the rectangular and triangular profile as optimal, respectively. Even if only simple, homogeneous, and not necessarily realistic geometrical shapes have been considered in this example, the triangular and rectangular profiles relate very well with common profiles for structural fire safety, trapezoidal or rectangular (RHS) hollow section filled with light concrete.

This simple example for the identification of an optimum steel profile points out the need for developing a unified structural design approach that takes all design requirements into account already in the initial design stage. The main objective of this work is to present a systematic way of taking fire safety related considerations into account in the early stages of structural design. The

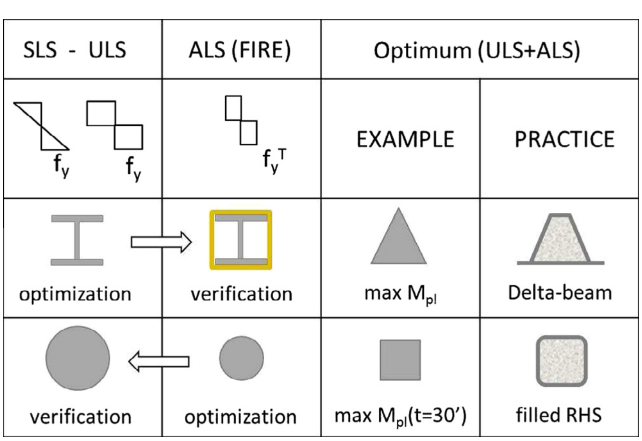

Fig. 1. Optimization of steel beam profiles at the different limit states.

authors acknowledge that this goal is a huge, complicated and challenging endeavor and hence the present work shall only be seen as a first step in this direction.

1.2. Background and method

The approach is based on topology optimization, a systematic tool for structural and mechanical design initiated by Bendsøe and Kikuchi [4] and since then extended to all kinds of other applications [5]. The approach is based on an iterative procedure including finite element analyses, gradient computations and design updates by Mathematical Programming approaches, where the design variables represent relative material density in each finite element used to discretize the design domain. In this way, one can obtain optimized structures represented by bit or voxel-maps without any restrictions on geometrical freedom. If needed, one may impose various kinds of length-scale control or robustness to manufacturing variations [6,7]. The literature on topology optimization is abundant and here we only list a few references of relevance to the present work. Topology optimization for thermal loading was initiated by Rodrigues and Fernandes [8] and extended to material design by Sigmund and Torquato [9] and to MEMS structures [10]. Convection effects have been included first in topology optimization of micromechanisms [11], and later in the design of general multiphysical systems [12–14]. Topology optimization for transient problems was developed for dielectric problems [15–17], thermal problems [18] and crashworthiness problems [19].

The topic of topology optimization for structural fire safety has seemingly not been the subject of much research, but a simple approach is suggested by Diaz and Benard [20]. Based on an uncoupled static mechanical problem and a steady-state heat transfer problem, the standard minimum compliance problem is extended with a maximum temperature constraint. Operating with two materials, a structural material and a thermally insulating material, it is shown how the latter will encase the former in order to protect it from heat.

Herein, another method is presented based on a weakly coupled static mechanical problem and transient heat transfer problem, in which the pursuit of maximum stiffness is constrained by a time-dependent structural degradation. The degradation starts from the surfaces exposed to fire and eats more and more of the structure as time passes and the material points reach a certain temperature. This simplified, and so far rather academic, formulation is used to obtain topologies that are capable of resisting heat controlled degradation for a given duration of time.

1.3. Structure of the paper

Section 2 introduces the design approaches used in structural fire safety and presents the simplified fire and material model used in the study. Section 3 gives details on the topology optimization formulation, finite element analysis and sensitivity analysis as well as on regularization schemes for ensuring stable topology optimization solutions. Section 4 demonstrates the approach by two